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ABSTRACT

Bargmann's test for examining the statistical significance of simple structure in factor analysis, an extension of the original significance tables, and the application of the significance test to several noted factor analytic findings are described. Using Bargmann's test, only 2 of 25 factor analytic studies reviewed are considered acceptable. Sixteen of the 25 studies did not produce a single statistically well defined hyperplane for any factor. It is concluded that more extensive rotations are needed and that the appropriateness of the original variables with respect to the content domain sampled be re-examined. The establishment of well-defined simple structures are required for replication and invariance of factor structures. (Author/MH)

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Application of a Precise Significance Test for Simple Structure to Some Important Structural Researches

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Abstract

The present paper describes Bargmann's test for examining the statistical significance of simple structure in factor analysis, reports an extension of the original significance tables, and applies the significance test to several noted factor analytic researches. As presently demonstrated, the test in actual usage is a severe critic of previously obtained factor analytic results. These findings indicate the need for more extensive rotations and further suggest that the appropriateness of the original variables with respect to the content domain sampled should be re-examined. Replication and invariance of factor structures require the establishment of well-defined simple structures.

Application of a Precise Significance Test for Simple Structure to Some Important Structural Researches

Introduction

Purpose

Factor analysis, as an analytic tool, has been widely used in educational and psychological research as a means of summarizing the interrelationships among variables in order to provide a conceptual understanding of a particular domain and the corresponding data matrix. Because of its widespread usage, it is important to demonstrate the adequacy and, thus, the interpretability of obtained factor analytic results. The purpose of the present paper is to (1) describe Bargmann's (1955) test for examining the statistical significance of simple structure in factor analysis, (2) report an extension of Bargmann's original statistical tables, and (3) apply the significance test to several factor analytic findings.

Background

Simple structure was first conceptualized by Thurstone (1935) in order to provide a psychologically meaningful solution to an original factor extraction, i.e., the unrotated factor matrix. In essence, the aim of simple structure is to yield a parsimonious solution consisting of each of the n variables loading on as few of the k factors as possible. Thurstone (1947) maintained that the results yielded by rotating a factor matrix, i.e., reference vector structure matrix, to simple structure should be evaluated by five criteria:

(1) Each row of the factor matrix should have at least one zero loading;

(2) Each column of the factor matrix should contain a set of k linearly independent variables whose factor loadings are zero;

(3) For every pair of columns of the matrix, there should be several variables whose factor loadings are zero in one column but not in the other;

(4) For every pair of columns of the factor matrix, a large proportion of variables should have zero loadings in both columns.

(5) For every pair of columns, there should be only a small number of variables with non-zero loadings in both columns.

When these criteria are met, the obtained simple structure is considered unique and, as such, justifies interpretation.

In employing Thurstone's simple structure definition, with an apparent emphasis on the second criterion, Bargmann derived mathematical probability functions addressing simple structure in terms of columns of the factor matrix. It should be noted that Bargmann's derivations apply most adequately to those factor analyses which result in an almost orthogonal simple structure and are regarded as minimal requirements for oblique simple structure. According to Thurstone, each column of the factor matrix is determined by a hyperplane, a plane in (k-1) dimensional space. Geometrically, a hyperplane through the origin of the total configuration of the k co-ordinate system is determined by (k-1) factor vectors. When these (k-1) vectors themselves are also contained in a specific hyperplane, the vectors have zero loadings. Since the aim of rotation is to overdetermine the (k-1) hyperplanes, the number of zero entries in each column of the n X k factor matrix should be equal to or greater than k. Therefore, overdetermination concerns the number of points in hyperspace falling within the hyperplane more frequently than would be expected due to chance occurrence (Cattell, 1978).

Although simple structure is sought in the reference vector structure, hyperplane counts are determined by the factor pattern (Gorsuch, 1974). The column values of the factor pattern are proportional to those in the reference vector structure matrix; these columns are differentially proportional except in the case of orthogonality when the two matrices are identical. Additionally, applying a constant hyperplane width to the reference vector structure matrix will result in a varying hyperplane width being applied to the factor pattern matrix (Cattell, 1978). Consequently, since factor interpretation is based on the factor pattern matrix, the significance test for simple structure is carried out on this factor matrix.

Bargmann's exact mathematical derivations are available in his early publication for the interested reader. In the publication, tables were provided for testing the statistical significance of simple structure for 2 to 12 factors over a range of 70 variables and for six probability levels ranging from .50 to .001. Contained in the tables were the number of variables appearing in the hyperplane of width $\pm$.10 for any one factor corresponding to a specific probability level, number of variables, and number of factors.

Given the size of contemporary factor analytic experiments, the number of factors and variables comprising Bargmann's original tables is no longer sufficient. Furthermore, the original article in German has had limited circulation and, except by Cattell and co-workers, appears to have been neglected in practical use.

The Present Investigation

Method

In view of the preceding considerations, the present authors (Sine & Kameoka, 1978) wrote a self-contained Fortran computer program using Bargmann's equations and probability expression to generate exact probabilities for at least r variables appearing in a hyperplane of width ah for n variables and k factors. For a ±.10 hyperplane width, Bargmann's original tables were extended to provide an increased number of variables, factors, and specific number of probability points.

In using the tables, one must examine the number of zero-loadings contained in each factor of the factor pattern. Variable loadings must be divided by the square root of their respective communalities in order to determine whether the loadings, upon being adjusted for communality size, still fall in the hyperplane. The number of variables whose adjusted loadings fall within the hyperplane of a factor is used to enter the probability tables to derive the statistical significance of the obtained simple structure for the factor. Adequately determined hyperplanes justify matching and interpretation of factors.

Application of Bargmann's significance test for simple structure

Bargmann's significance test for simple structure was applied to the findings of 20 factor analytic studies, 19 of which were selected from a review of journal articles published in volumes 1-13 of Multivariate Behavioral Research. The articles selected for the present examination were among those which provided complete factor patterns including all factor loadings and the associated communalities. These articles and the results

of the significance tests are summarized in Tables I and II. The selected studies varied with respect to content domain, size, and type of factor analytic methods and procedure used in the respective research. It should be noted here that the present investigation does not address issues regarding factor extraction methods, communality estimation, number of factors extracted, and so forth.

Insert Table I About Here

Table I briefly describes the research topics of the 20 studies, rotational methods employed, as well as the numbers of variables, subjects, and factors. The results of the present application of Bargmann's significance test for simple structure are shown in Table II which provides seven summary statistics. These include (1) the probability range for the k factors of each study, (2) median probability of the k factors, (3) average probability of the k factors, (4) percent of the factors with $p < .05$, (5) overall percent of zero-loadings in the factor pattern adjusted for communality size, (6) average number of adjusted zero loadings per factor, and (7) the interpolated probability of this average. Probabilities represent degree of overdetermination of a factor's hyperplane, i.e., the probability of at least r vectors falling in the critical region of $\pm.10$ by chance. In order to protect against rounding error, especially when only two digit loadings and communalities were reported in the respective studies, the boundaries of the critical region (i.e., +.10 and -.10) were not considered part of the hyperplane. Thus, a .10 loading (adjusted and unadjusted loadings) was considered outside the critical region and the hyperplane.

Insert Table II About Here

Finally, the last column of Table II lists the overall percent of zero loadings in the unadjusted factor matrix. These percentages of unadjusted zero loadings are commonly reported in factor analytic studies.

In order to demonstrate the consequences of subjecting factor analytic findings to Bargmann's significance test, four of the 20 studies summarized in Tables I and II are discussed in further detail. The first two studies reported orthogonal factorial solutions while the third and fourth studies reported obliquely rotated factor matrices.

The purpose of Holtzman and Bitterman's (1956) study was to identify common factors among a variety of measures purportedly predictive of adjustment to stress. Twenty-five variables selected for analysis included ratings and tests of personality, performance measures in stressful situations, as well as perceptual, psychophysiological, and biochemical measures. Intercorrelation of the 25 variables was factor analyzed by Thurstone's centroid method followed by an orthogonal rotation to simple structure. Seven factors were extracted and interpreted. In applying Bargmann's test to each column of the 25 by 7 rotated factor matrix, the present authors found a minimum of six and a maximum of nine adjusted zero loadings which represent probabilities ranging from .98 to .72. Therefore, all of the findings were non-significant and the hyperplanes, not adequately defined. For this size factor matrix, at least 13 zero loadings per factor are required to yield a significant hyperplane at the .05 level.

Jackson and Lay's (1968) factor analytic sutdy was primarily designed to determine the extent to which personality scale score variance is attributable

to scale content and response styles of acquiescence and desirability, as well as to other confounds representing non-content biases. Four subscales of five personality content scales, measures of acquiescence and desirability, and an adjective checklist consisting of alternatively stated true and false, positively and negatively worded items, were administered to 158 female subjects. The 30 by 30 intercorrelation matrix was factor analyzed by the principal axes method and the nine factors extracted were rotated to a varimax criterion. Application of Bargmann's significance test for simple structure showed that a minimum of 12 and a maximum of 17 adjusted zero loadings were found among the nine interpreted factors. Probabilities for finding at least the above number of zero loadings for a factor study of the present size range from .97 to .03, respectively. Simple structures demonstrated by only two of the nine factors are significant at the .05 level, while two other factors reach a probability level of .08. Probabilities of the remaining factors reaching their positions by chance are greater than .15. At least 17 zero loadings per factor are required for the overdetermination of the hyperplane at the .05 level of significance.

Mos, Wardell, and Royce (1974) factor analyzed 26 variables from tests marking aspects of psychological differentiation and cognitive abilities. The study was designed to replicate established "element" and "form articulation" factors and to relate these factors to cognitive abilities. Test data from 80 subjects were intercorrelated and factor analyzed by the alpha method. Eight factors with eigenroots greater than one were extracted and rotated to varimax criterion. The varimax transformation was subsequently rotated by a Promax procedure and simple structure yielded by Promax with power four was interpreted. The significance test showed that at least 15

adjusted zero loadings are required to reach significance at the .05 level. The eight rotated factors contained a minimum of seven and a maximum of 19 adjusted zero loadings which represent probabilities ranging from .99 to .0001. Two of the eight factors resolved in significant hyperplanes at the .05 level.

The Klinger and Saunders' (1975) factor analytic study of 110 items from nine subtests of the WAIS for 916 "normal" students was intended to answer questions of dimensionality and the implications of the factorial structure for subtest-based diagnosis and personality assessment. They factor analyzed an 82 x 82 matrix of tetrachoric covariances and 28 additional variables were included as extension variables (Dwyer, 1937). Fifteen factors were extracted and initially rotated by the normal equamax method to an orthogonal approximation of simple structure. An isopromax oblique rotation was then performed. Application of Bargmann's test showed that a minimum of 40 and a maximum of 66 adjusted zero loadings were found among the 15 factors. Probabilities for finding at least the above number of zero loadings range from .68 to .00001, respectively. Simple structures demonstrated by eight of the 15 factors are significant at the .05 level and, thus, are adequately defined. At least 50 zero loadings on a factor are required for the overdetermination of the hyperplane (contained within $\pm$.10) at the .05 level of significance.

Discussion

As shown in Table II, only one of the 25 factor matrices yielded, for all factors, overdetermined hyperplanes at the .05 level of significance. In fact 16 of the matrices did not produce a single statistically well-defined hyperplane for any factor. In short, the majority of factor analytic results evaluated in the present investigation did not reach statistical significance

by Bargmann's test. As Cattell (1978) noted, if the Bargmann test for simple structure was consistently applied to factor analytic researches, a majority of studies "would have their conclusions wiped out thereby--which is perhaps why a test of the significance of the obtained simple structure is so rarely published." (Cattell, 1978, p. 196).

Cattell (1973, 1978) maintained that a simple structure significance test is one of the necessary conditions for interpreting factor analytic studies and the absence of overdetermined rotated resolutions is the main cause of poor factor matchings of which critics of factor analysis complain. The present authors feel that conclusions drawn from statistically inadequate simple structures are potentially misleading and should be held suspect. Non-significant simple structures suggest that further rotations may be necessary to define hyperplanes more adequately and may further suggest that the appropriateness of the original variables with respect to the content domain sampled should be further examined. Although it is more difficult to obtain clearer hyperplanes using orthogonal as compared to oblique rotations, perhaps the inadequacy of the above solutions may suggest the inappropriateness of the orthogonal transformations in the given studies (c.f., Cattell & Dickman, 1962). In this regard, those studies using oblique transformations fared slightly better than those employing orthogonal transformation. However, it is difficult to draw any firm conclusions regarding the appropriateness of these transformations based on the present findings because of the variations among the studies.

As previously noted, the overall percent of loadings in the hyperplanes (reported in the last column in Table II) is customarily used as an indication of the adequacy of obtained simple structures. If, as suggested by Cattell

(1978), most adequate designs require from a 60 to 80 percent hyperplane count, only two of the 25 factor analytic results may be considered acceptable. Total hyperplane counts per study across these researches ranged from 19 to 81 percent with a median of only 46 percent. Furthermore, when factor pattern loadings are adjusted for the variables' communality sizes this overall count dropped considerably in some cases due to low communalities. Hyperplane counts are also related to number of variables, number of factors, hyperplane width, and degree of obliquity among factors. Therefore, as Gorsuch (1974) stated, ". . . a high hyperplane count can be obtained by extracting many factors from few variables with low reliability and rotating to a highly oblique position. No level of hyperplane count can be set as that defining "good simple structure" unless the characteristics of the study are known in detail." (Gorsuch, 1974, p. 166). Bargmann mathematically incorporated these considerations into his test of the significance of simple structure, and in the case of highly oblique factors, Bargmann suggested that more stringent levels of significance than $p < .05$ are essential.

Summary

The present investigation demonstrated a lack of statistically significant simple structures in the majority of the factor matrices reported by the 20 sampled studies. Such lack of factor definition may suggest the need for more refined rotational methods, more thorough samplings of content domains, and consideration of potential obliquity among factors. To the extent that a well-defined hyperplane optimally yields uniquely stable, replicable, invariant factor definition of any content domain, it is incumbent upon the factor analyst to provide well-defined simple structures.

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Table I. Characteristics of the Factor Analytic Studies

Study	Research Topic	No. of Ss	No. of Variables	No. of Factors	Rotational Method
1. Boe, Gocka, & Kogan (1966)	interpersonal perception	390[a]	64	18	varimax
2. DeMille & Hirschberg (1972)	conceptual domains	257	31	8	orthogonal to congruence
3. Guilford & Hoepfner (1966)	divergent-production abilities	205	59	25	orthogonal least squares
4. Hetrick, Lilly, & Merryfield (1968)	creativity, intelligence, & personality	196	30	9	varimax
5. Holtzman & Bitterman (1956)	adjustment to stress	135	25	7	orthogonal (unspecified)
6. Horn, Wanberg, & Appel (1973)	MMPI	1884	33	6	varimax
7. Mundal & Singh (1971)	intelligence, personality, interest & achievement	271	31	12	maxplane
8. Ismail & Young (1977)	a. exercise on biochemical & personality - pre	58	15	6	varimax
	b. exercise on biochemical & personality - post	58	15	6	varimax
9. Jackson & Lay (1968)	personality scale content	158	30	9	varimax
10. Jones (1976)	concept learning & ability	102	22	6	orthogonal (unspecified)
11. Klingler & Saunders (1975)	WAIS	916	110	15	isopromax
12. Magnusson & Ekehammar (1973)	situations	432[b]	36	5	varimax
13. McCartin & Meyers (1966)	semantic factors	100	23	8	biquartimin
14. Milton & Lipetz (1968)	a. EPPS - males	150	15	5	varimax
	b. EPPS - females	150	15	5	varimax
15. Mos, Wardell, & Royce (1974)	cognitive styles	80	27	8	promax
16. Royce, Yeudall, & Bock (1976)	human brain damage	176	54	13	varimax
17. Saunders (1969)	a. Activities Index	1076	30	13	equamax
	b. College Characteristics Index	1076	30	11	equamax
18. Swartz & Moran (1968)	a. word associations - 9 years	102	9	3	varimax
	b. word associations - 12 years	110	9	4	varimax
19. Williams, Lipman, Rickels, Covi, Uhlenhuth, & Mattsson (1968)	symptoms of anxious neurotics	1115	58	5	varimax
20. Ziegler & Atkinson (1973)	a. political attitudes - hi info.	195	16	4	oblimin
	b. political attitudes - low info.	174	16	5	

[a] Based on 26 subjects x 5 sets x 3 occasions
[b] Based on 12 subjects x 36 situations

Table II. Results of Simple Structure Significance Test

Study	Probability Range	Median Probability	Average Probability	% of Factors $p < .05$	Overall % Adjusted Zero Loadings	Average No. Adjusted Zero Loadings Per Factor	Associated Probability	Overall % of Unadjusted Zero Loadings
1. Boe, Gocka, & Kogan (1966)	.99 - .01	.81	.64	6%	32%	3.2	.75	55%
2. DeMille & Hirschberg (1972)	.99 - .35	.82	.78	0%	32%	10.0	.89	46%
3. Guilford & Hoepfner (1966)	.99 - .30	.99	.93	0%	30%	25.7	.99	52%
4. Hetrick, Lilly, & Merryfield (1968)	.99 - .34	.88	.81	0%	37%	11.0	.88	44%
5. Holtzman & Bitterman (1956)	.99 - .72	.72	.83	0%	33%	8.3	.84	46%
6. Horn, Wanberg, & Appel (1973)	.99 - .72	.99	.94	0%	19%	6.3	.98	24%
7. Hundal & Singh (1971)	.99 - .05	.86	.68	8%	47%	14.6	.84	56%
8. Ismail & Young (1977) (a)	.99 - .07	.99	.76	0%	33%	5.0	.99	38%
(b)	.99 - .52	.92	.86	0%	33%	5.0	.99	38%
9. Jackson & Lay (1968)	.97 - .03	.18	.27	22%	49%	14.8	.21	56%
10. Jones (1976)	.99 - .15	.77	.66	0%	32%	7.0	.81	38%
11. Klingler & Saunders (1975)	.68 - .00001	.04	.20	53%	45%	49.5	.05	81%
12. Magnusson & Ekehammar (1973)	.005 - .0004	.0004	.002	100%	45%	16.2	.001	52%

Table II (continued). Results of Simple Structure Significance Test

Study	Probability Range	Median Probability	Average Probability	% of Factors $p < .05$	Overall % Adjusted Zero Loadings	Average No. Adjusted Zero Loadings Per Factor	Associated Probability	Overall % of Unadjusted Zero Loadings
13. McCartin & Meyers (1966)	.97 - .007	.15	.30	38%	53%	12.1	.20	61%
14. Milton & Lipetz (1968) (a)	.99 - .22	.83	.71	0%	33%	5.0	.83	44%
(b)	.99 - .83	.99	.96	0%	24%	3.6	.99	45%
15. Mos, Wardell, & Royce (1974)	.99 - .0001	.77	.58	25%	43%	11.5	.49	54%
16. Royce, Yeudall, & Bock (1976)	.99 - .007	.95	.65	8%	38%	20.3	.88	47%
17. Saunders (1969) (a)	.99 - .54	.99	.92	0%	44%	13.3	.99	55%
(b)	.99 - .90	.99	.98	0%	30%	8.9	.99	40%
18. Swartz & Moran (1968) (a)	.99 - .99	.99	.99	0%	11%	1.0	.99	19%
(b)	.99 - .99	.99	.99	0%	22%	2.0	.99	31%
19. Williams, Lipman, Rickels, Covi, Uhlenhuth, & Mattsson (1968)	.99 - .0001	.88	.62	25%	25%	14.5	.87	34%
20. Ziegler & Atkinson (1973) (a)	.99 - .83	.91	.91	0%	17%	2.8	.99	23%
(b)	.86 - .55	.86	.76	0%	31%	5.0	.86	34%